

University of Groningen

Boundary Scattering Modified One-Dimensional Weak Localization in Submicron GaAs/AlGaAs Heterostructures

Houten, H. van; Beenakker, C.W.J.; Wees, B.J. van; Mooij, J.E.

Published in:
Surface Science

DOI:
[10.1016/0039-6028\(88\)90677-2](https://doi.org/10.1016/0039-6028(88)90677-2)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1988

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Houten, H. V., Beenakker, C. W. J., Wees, B. J. V., & Mooij, J. E. (1988). Boundary Scattering Modified One-Dimensional Weak Localization in Submicron GaAs/AlGaAs Heterostructures. *Surface Science*, 196(1). [https://doi.org/10.1016/0039-6028\(88\)90677-2](https://doi.org/10.1016/0039-6028(88)90677-2)

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

BOUNDARY SCATTERING MODIFIED ONE-DIMENSIONAL WEAK LOCALIZATION IN SUBMICRON GaAs/AlGaAs HETEROSTRUCTURES**H. VAN HOUTEN, C.W.J. BEENAKKER***Philips Research Laboratories, 5600 JA Eindhoven, The Netherlands***B.J. VAN WEES and J.E. MOOIJ***Delft University for Technology, 2628 CJ Delft, The Netherlands*

Received 29 May 1987; accepted for publication 30 July 1987

The influence of boundary scattering on the one-dimensional weak localization of electrons is studied experimentally, in a submicron width GaAs/AlGaAs heterostructure. The weak field magnetoresistance is measured at temperatures between 100 mK and 14 K. It is shown that the usual Al'tshuler–Aronov theory is inapplicable because of boundary scattering effects in the high mobility material. The observed effects can be accounted for by extensions of a recent theory of Dugaev and Khmel'nitskii. The analysis shows that scattering from the channel boundaries is predominantly specular, rather than diffuse.

1. Introduction

We have performed magnetoresistance experiments on a laterally restricted GaAs/AlGaAs heterostructure, fabricated using a shallow mesa etch technique described earlier [1]. Similar experiments on quasi-one-dimensional transport have recently been reported [2–4]. In our sample the elastic mean free path l_e (associated with impurity scattering) is larger than the channel width W . As a consequence, the transport properties depend on the nature of the boundary scattering and can no longer be described by the Al'tshuler–Aronov (AA) theory for dirty metals [5], valid in the regime $l_e \ll W$. In this paper an experimental study of the new high mobility regime is reported. The data are analyzed by means of an extension [6] of the Dugaev–Khmel'nitskii (DK) theory [7] for clean metal films, which allows us to discriminate between diffuse and specular boundary scattering.

The GaAs/AlGaAs heterostructure studied consists of a long narrow channel which connects two broad two-dimensional electron gas regions. The channel length L is 10 μm , and the width defined by the mesa structure is 0.5 μm . The effective width may be considerably smaller due to sidewall depletion [4]. The channel boundaries in our sample are thus not physical boundaries but rather confinement potential walls. From Shubnikov–de Haas experiments [8] the electron gas den-

sity in the narrow channel is estimated to be $2.5 \times 10^{15} \text{ m}^{-2}$, which is a factor of 2 lower than in the broad regions. We have measured the negative weak field magnetoresistance for temperatures between 100 mK and 14.3 K. Preliminary data on this sample for fields up to 1.5 T have been reported earlier [1]. The magnetic field dependence of the conductance for 4 temperatures is shown in fig. 1 for fields up to 0.2 T. The observed effect is clearly a one-dimensional weak localization effect, since the 2D weak localization theory would predict a saturation of the effect if the magnetic length $l_c \equiv \sqrt{\hbar/eB}$ becomes comparable to l_e , which implies much lower saturation fields than the typically observed fields of 0.2 T. (The electron-electron interaction effect is generally found to be field independent in this field range [2–4].) Although the usual AA-theory [5] for 1D weak localization fits our data well, this analysis is *inconsistent* since the resulting parameter values ($W \approx 60 \text{ nm}$, $l_c \approx 600 \text{ nm}$) violate the criterion $l_c \ll W$ for its applicability. Because of the large mean free path we have to explicitly consider boundary scattering effects.

2. Boundary scattering modified weak localization

In the semiclassical description of weak localization [9] the conductance $G(B)$ in a magnetic field is given by

$$G(B) = G_0 - \frac{2e^2}{\pi\hbar} \frac{D}{L} \int_0^\infty dt C(t) e^{-t/\tau_\phi} e^{-t/\tau_H}. \quad (1)$$

Here G_0 is a field independent term, D is the diffusion coefficient, and τ_ϕ and τ_H are the phase relaxation times associated with respectively inelastic collisions and the magnetic field. The quantity $C(t)$ represents the fraction of electrons which, after a time t , has returned to the origin. In the diffusion approximation $C(t) = (4\pi Dt)^{-1/2}$. This approximation breaks down for short times, since electrons must have experienced at least a single collision before they can return. Even if there are no complications associated with boundary scattering, short time corrections are important if τ_c and τ_ϕ are comparable. We can correct for this effect in an ad hoc way by introducing the additional factor $(1 - e^{-t/\tau_c})$ in $C(t)$, thereby excluding those electrons which have not yet been scattered elastically. This gives

$$G(B) = G_0 - \frac{e^2}{\pi\hbar} \frac{\sqrt{D}}{L} \left[\left(\frac{1}{\tau_\phi} + \frac{1}{\tau_H} \right)^{-1/2} - \left(\frac{1}{\tau_\phi} + \frac{1}{\tau_H} + \frac{1}{\tau_c} \right)^{-1/2} \right]. \quad (2)$$

In the regime $\tau_c \ll \tau_\phi$ the second term between square brackets (resulting from the short time correction) can be neglected, as in the AA-theory. However, in our electron gas channel ρ_c and τ_ϕ are comparable (typically $\tau_\phi \approx 4\tau_c$), and short time contributions are important. These would merit a more detailed investigation.

We now turn to the influence of boundary scattering. In the AA-theory the walls only serve to restrict the lateral diffusion, and the nature of the wall collisions is

irrelevant. For $l_c > W$, however, the walls directly affect the motion of the electrons, and the boundary scattering has to be treated explicitly [7]. We have calculated the phase relaxation time τ_B and find [6] for magnetic fields such that $l_c > W$ that

$$\tau_B = \frac{l_c^4}{K_1 W^3 v_F} + \frac{l_c^2 \tau_c}{K_2 W^2}. \quad (3)$$

Here v_F is the Fermi velocity, and the coefficients are $K_1 = 0.11$ and $K_2 = 0.23$ for specular scattering, and $K_1 = 1/4\pi$ and $K_2 = 1/3$ for diffuse scattering. (For comparison we note that in the AA-theory $\tau_B = 6l_c^4/W^2 v_F^2 \tau_c$.) Eq. (3) is a numerically obtained interpolation formula which agrees with analytical results in the limit of small or large magnetic fields. Channel width variations will cause additional phase randomization for strong magnetic fields. It can be estimated [6] that if width variations are moderate, as in our sample, we can neglect this effect for fields such that $l_c > W$. Substitution of eq. (3) into eq. (2) yields the desired expression for the magnetoconductance. The diffusion coefficient appearing in this equation strongly depends on the boundary scattering. We have calculated D for a narrow 2D electron gas (cf. ref. [10]) and find for diffuse scattering

$$D = \frac{1}{2} v_F l_c \left(1 - \frac{4l_c}{\pi W} \int_0^1 ds s^2 \{ 1 - \exp[-(1-s^2)^{-1/2} W/l_c] \} \right), \quad (4)$$

while $D = \frac{1}{2} v_F l_c$ for specular scattering. In the limit $l_c/W \rightarrow \infty$, eq. (4) simplifies to $D = (v_F W/\pi) \ln(l_c/W)$. These are semi-classical formulae, in which the discreteness of the one-dimensional subbands in the channel is ignored. It would be of interest to study the influence of the subband structure on the magnetoresistance (cf. ref. [11]) since in these semiconductor channels only a few subbands are typically occupied [8].

3. Results

The data are analyzed in terms of the equations given in the previous section. Two of the three unknown parameters (W , τ_c and τ_ϕ) can be eliminated using estimated values for the classical conductance ($G_{cl} = (me^2/\pi\hbar^2)(W/L)D = 18 \times 10^{-6} \Omega^{-1}$, as obtained from extrapolation of a plot of $G(0)$ versus $T^{-1/2}$) and for the saturation value of the magnetoconductance,

$$G(\infty) - G(0) = \frac{e^2}{\pi\hbar} \frac{\sqrt{D}}{L} \left[\tau_\phi^{1/2} - \left(\frac{1}{\tau_\phi} + \frac{1}{\tau_c} \right)^{-1/2} \right]. \quad (5)$$

At 4.0 K we estimate $G(\infty) = 13.9 \times 10^{-6} \Omega^{-1}$ (see fig. 1). Despite the uncertainties in $G(\infty)$ this procedure was chosen instead of a two or three parameter fit because of the limited field range available for the fit. (We checked that variations of $\sim 20\%$ in $G(\infty)$ do not significantly affect the results given below.) The third

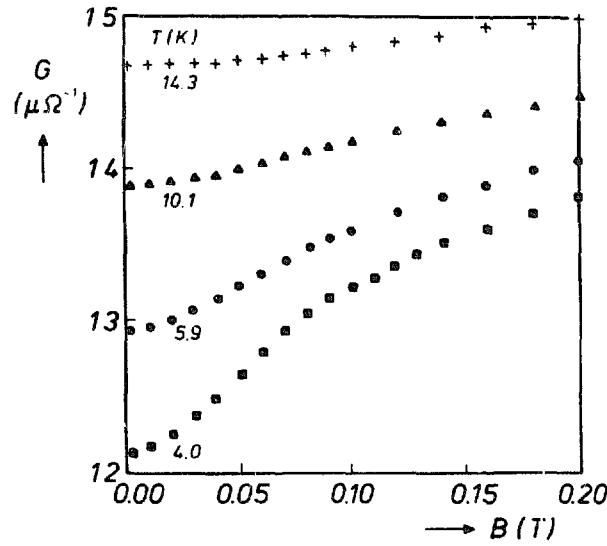


Fig. 1. Perpendicular field magnetoconductance in a $0.5 \mu\text{m}$ wide GaAs/AlGaAs heterostructure for 4 temperatures.

parameter is obtained by a fit, considering only data points for which $l_c > W$ (see section 2). In fig. 2 the results for the 4.0 K data are shown. For specular scattering a reasonable fit is obtained, with $W = 106 \text{ nm}$, $l_c \equiv v_F \tau_c = 351 \text{ nm}$ and $l_\phi \equiv \sqrt{D\tau_\phi} = 450 \text{ nm}$. For diffuse scattering the data *cannot be fitted* with values of l_c smaller than $1 \mu\text{m}$ – which is the value for the wide channels on our sample. (Even for an unphysically larger mean free path the fit is poorer than for specular scattering.) The physical reason that we can discriminate by means of this theory between the

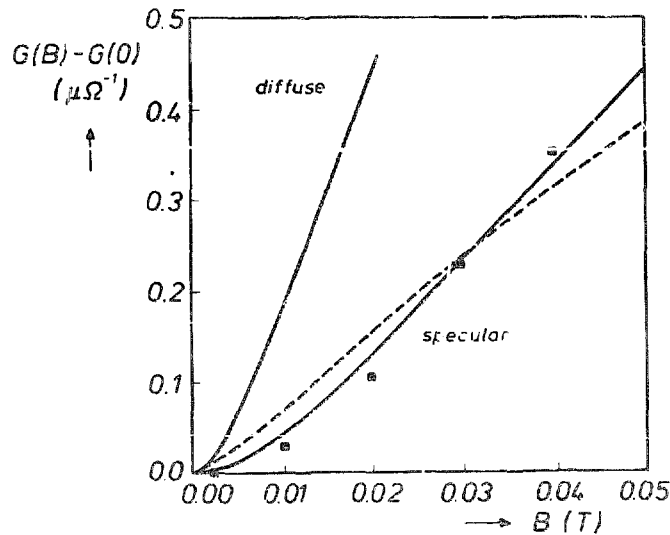


Fig. 2. Analysis of the 4.0 K magnetoconductance data. Solid lines are best fits of eq. (2) for diffuse and specular boundary conditions with l_c smaller than the bulk value of $1 \mu\text{m}$. (Dashed line is for diffuse scattering with unrealistically high $l_c = 7 \mu\text{m}$.)

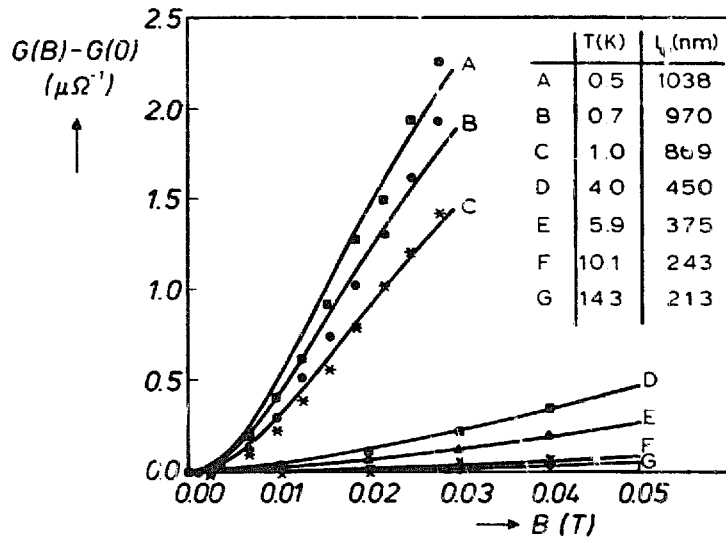


Fig. 3. Magnetoconductance data between 500 mK and 14.3 K. At still lower temperatures the effect saturates (not shown). The solid curves result from the specular scattering theory, with l_e as fit parameter.

two types of boundary scattering is that the conductance depends on the magnetic field through the diffusion length $\sqrt{D\tau_B}$ (see eq. (2)). Since the relaxation time τ_B is rather insensitive to the type of boundary scattering (eq. (3)), the resulting diffusion length strongly depends on whether the scattering is diffuse or specular. Finally, in fig. 3 data are shown for temperatures between 0.5 K and 14 K, fitted to the specular scattering theory with the values for W and l_e given above. Again, a reasonably good fit is found. The values for l_e given in the figure are consistent with the expressions given by Zheng et al. [3], but in view of the uncertainties in the modelling of the short time behavior (in eq. (2)) these values may not be very accurate. The width found for this narrow channel is a factor of 5 smaller than the etched width of $0.5 \mu\text{m}$. This result agrees with the value obtained from an analysis of the magnetic depopulation of 1D subbands in higher magnetic fields [8]. Similar large sidewall depletion effects have been found by Choi et al. [4]. We find from l_e a diffusion coefficient $D=0.039 \text{ m}^2/\text{s}$, which implies a channel mobility of $4 \text{ m}^2/\text{V}\cdot\text{s}$. This is only a factor of 2 smaller than in the wide 2D electron gas regions. It can thus be concluded that our shallow mesa etch sample fabrication method [1] does not introduce much additional scattering.

In conclusion, we have presented experimental data on 1D weak localization in a new high mobility regime. Theoretical expressions for boundary modified weak localization are given, and it is concluded from the analysis of the data that the sidewall scattering is specular, rather than diffuse.

Acknowledgements

The assistance of J.W. van Gastel and M.E.I. Broekaart in performing the experiments is gratefully acknowledged. We thank Professor M.F.H. Schuurmans for

valuable advise. Part of the work belonged to the research program of the Stichting Fundamenteel Onderzoek der Materie, FOM, and was financially supported by ZWO.

References

- [1] H. van Houten, B.J. van Wees, M.G.J. Heyman and J.P. André Appl. Phys. Letters 49 (1986) 1781.
- [2] T.J. Thornton, M. Pepper, H. Ahmed, D. Andrews and G.J. Davies, Phys. Rev. Letters 56 (1986) 1198.
- [3] H.Z. Zheng, H.P. Wei, D.C. Tsui and G. Weimann, Phys. Rev. B34 (1986) 5635.
- [4] K.K. Choi, D.C. Tsui and K. Alavi, Appl. Phys. Letters 50 (1987) 110.
- [5] B.L. Al'tshuler and A.G. Aronov, Pis'ma Zh. Eksperim. Teor. Fiz. 33 (1981) 515 [JETP Letters 33 (1981) 499].
- [6] C.W.J. Beenakker and H. van Houten, to be published.
- [7] V.K. Dugaev and D.E. Khmel'nitskii, Zh. Eksperim. Teor. Fiz. 86 (1984) 1784 [Soviet Phys.-JETP 59 (1984) 1038].
- [8] H. van Houten, B.J. van Wees, J.E. Mooij, G. Roos and K.-F. Berggren, 3rd Conf. on Superlattices, Microstructures and Microdevices, Chicago, 1987, Superlattices Microstruct., to be published.
- [9] S. Chakravarty and A. Schmid, Phys. Rept. 140 (1986) 193.
- [10] K. Fuchs, Proc. Cambridge Phil. Soc. 34 (1938) 100;
E.H. Sondheimer, Advan. Phys. 1 (1952) 1.
- [11] Z. Tesanovic, M.V. Jaric and S. Maekawa, Phys. Rev. Letters 57 (1986) 2760.